RESEARCH ACTIVITIES

Theoretical and Computational Molecular Science

It is our goal to develop new theoretical and computational methods based on quantum mechanics and statistical mechanics to predict and understand the structures, chemical reactions, and functions of molecules in gas and condensed phases including nano- and bio-systems.

Theoretical Studies on Heterogeneous Condensed Phase Dynamics

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Keywords Spatiotemporal Heterogeneous Dynamics, Liquids, Proteins

Nonlinear intermolecular interactions cause complicated motions in condensed phases, *e.g.* liquids and biological systems. These motions are spatially and temporally heterogeneous with a wide range of time and spatial scales and yield both static and dynamic properties of the systems. The spatiotemporal non-uniform motions known as dynamic heterogeneity are considered to be a clue to understand supercooled liquids and glass transition. Furthermore, heterogeneous reaction rates have been found in biological systems. Therefore, understanding of spatiotemporal heterogeneous dynamics is essential to the elucidation of the structure, thermodynamics, dynamics, and functions of the condensed phase systems.

We have investigated inter- and intra-molecular dynamics of water by using third-order nonlinear spectroscopy which can provide the detailed dynamics that are not available from conventional IR spectroscopy. We have examined the detailed fluctuations in water by calculating two-dimensional IR spectra of water. We have revealed the molecular mechanism of ultrafast energy relaxation, which is one of dynamical features of water, i.e. the fast energy relaxation is caused by the nonlinear strong coupling between the libration motion and other intra- and inter-molecular vibrational motions.

We have also investigated the dynamics of supercooled liquids. We quantified the lifetime of dynamic heterogeneity by introducing the three-time correlation function of density fluctuation, which is sensitive to the time evolution of dynamic heterogeneity. Our systematic analysis for various systems shows that the lifetime of dynamic heterogeneity is intimately related to configurational entropy and thus the temperature dependence of lifetime of dynamic heterogeneity is more sensitive to the fragility than that of α-relaxation time determined by one-time correlation function. In addition to the analysis of dynamic heterogeneity with multi-time correlation function, we have examined the molecular origin of anomalous temperature dependence of isobaric specific heat of water. The time scale involved in isothermal specific heat has been analyzed by analyzing complex specific heat. We examined the emergence of correlated motion in terms of the wavenumber (k) dependent complex specific heat and the shell-wise energy fluctuation.

We currently investigate how chemical reactions proceed in biological systems, *e.g.* clock protein KaiC, under complex fluctuations. We also examine the large conformational transitions and the time-dependent couplings between conformational dynamics in proteins by using the idea of multidimensional spectroscopy.

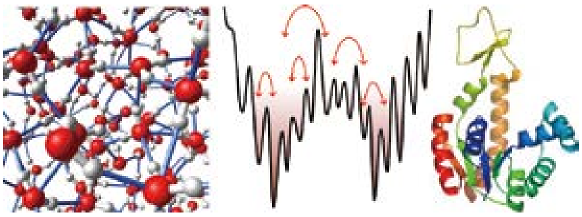

Figure 1. Schematic figure of rugged energy landscape (center) in supercooled water (left) and a biomolecule (right).

Selected Publications

- T. Yagasaki and S. Saito, *Acc. Chem. Res.* **42**, 1250–1258 (2009), *Annu. Rev. Phys. Chem.* **64**, 55–75 (2013). S. Imoto, S. Xantheas and S. Saito, *J. Chem. Phys.* **139**, 044503 (7 pages) (2013).
- K. Kim and S. Saito, *J. Chem. Phys. (Special Topic on Glass Transition)* **138**, 12A506 (12 pages) (2013).
- S. Saito, I. Ohmine and B. Bagchi, *J. Chem. Phys.* **138**, 094503 (7 pages) (2013).

1. Dynamic Heterogeneity in the Folding/ Unfolding Transitions of FiP35[1)]

Molecular dynamics simulations have become an important tool in studying protein dynamics over the last few decades. Atomistic simulations on the order of micro- to milliseconds are becoming feasible and are used to study the state-of-the-art experiments in atomistic detail. Yet, analyzing the high-dimensional-long-temporal trajectory data is still a challenging task and sometimes leads to contradictory results depending on the analyses. To reveal the dynamic aspect of the trajectory, here we propose a simple approach which uses a time correlation function matrix and apply to the folding/ unfolding trajectory of FiP35 WW domain [Shaw *et al.*, *Science* **330**, 341 (2010)]. The approach successfully characterizes the slowest mode corresponding to the folding/ unfolding transitions and determines the free energy barrier indicating that FiP35 is not an incipient downhill folder. The transition dynamics analysis further reveals that the folding/ unfolding transition is highly heterogeneous, *e.g.*, the transition path time varies by ~100 fold. We identify two misfolded states and show that the dynamic heterogeneity in the folding/ unfolding transitions originates from the trajectory being trapped in the misfolded and half-folded intermediate states rather than the diffusion driven by a thermal noise. The current results help reconcile the conflicting interpretations of the folding mechanism and highlight the complexity in the folding dynamics. This further motivates the need to understand the transition dynamics beyond a simple free energy picture using simulations and single-molecule experiments.

2. Couplings between Hierarchical Conformational Dynamics from Multi-Time Correlation Functions and Two-Dimensional Lifetime Spectra: Application to Adenylate Kinase[2)]

An analytical method based on a three-time correlation function and the corresponding two-dimensional (2D) lifetime spectrum is developed to elucidate the time-dependent couplings between the multi-timescale conformational dynamics in heterogeneous systems such as proteins. In analogy with 2D NMR, IR, electronic, and fluorescence spectroscopies, the waiting-time dependence of the off-diagonal peaks in the 2D lifetime spectra can provide a quantitative description of the dynamical correlations between the conformational motions with different lifetimes. The present method is applied to intrinsic conformational changes of substrate-free adenylate kinase (AKE) using long-time coarse-grained molecular dynamics simulations. It is found that the hierarchical conformational dynamics arise from the intra-domain structural transitions among conformational sub-states of AKE by analyzing the one-time correlation functions and one-dimensional lifetime spectra for the donor–acceptor distances corresponding to single-molecule Förster resonance energy transfer experiments with the use of the principal component analysis. In addition, the complicated waiting-time dependence of the off-diagonal peaks in the 2D lifetime spectra for the donor–acceptor distances is attributed to the fact that the time evolution of the couplings between the conformational dynamics depends upon both the spatial and temporal characters of the system. The present method is expected to shed light on the biological relationship among the structure, dynamics, and function.

3. Ultrafast Dynamics of Liquid Water: Energy Relaxation and Transfer Processes of the OH Stretch and the HOH Bend[3)]

The vibrational energy relaxation and transfer processes of the OH stretching and the HOH bending vibrations in liquid water are investigated via the theoretical calculation of the pump–probe spectra obtained from non-equilibrium molecular dynamics simulations with the TTM3-F interaction potential. The excitation of the OH stretch induces an instantaneous response of the high frequency librational motions in the 600–1000 cm^{-1} range. In addition, the excess energy of the OH stretch of a water molecule quickly transfers to the OH stretches of molecules in its first hydration shell with a time constant of ~50 fs, followed by relaxation to the HOH bends of the surrounding molecules with a time constant of 230 fs. The excitation of the HOH bend also results in the ultrafast excitation of the high frequency librational motions. The energy of the excited HOH bend of a water molecule decays, with a time constant of 200 fs, mainly to the relaxation of the HOH bends of its surrounding molecules. The energies of the HOH bends were found to transfer quickly to the intermolecular motions via the coupling with the high frequency librational motions. The excess energy of the OH stretch or the HOH bend relaxes to the high frequency intermolecular librational motions and eventually to the hot ground state with a time scale of ~1 ps via the coupling with the librational and translational motions. The energy relaxation and transfer processes were found to depend on the local hydrogen bonding network; the relaxations of the excess energy of the OH stretch and the HOH bend of four- and five-coordinated molecules are faster than those of a three-coordinated molecule due to the delocalization of the vibrational motions of the former (four- and five-coordinated molecules) compared to those of the later (three-coordinated molecules). The present results highlight the importance of the high frequency intermolecular librational modes in facilitating the ultrafast energy relaxation process in liquid water via their strong nonlinear couplings with the intramolecular OH stretching and HOH bending vibrations.

References

1) T. Mori and S. Saito, *J. Chem. Phys.* **142**, 135101 (7 pages) (2015).
2) J. Ono, S. Takada and S. Saito, *J. Chem. Phys., Special Topic: Multidimensional Spectroscopy* **142**, 212404 (13 pages) (2015).
3) S. Imoto, S. S. Xantheas and S. Saito, *J. Phys. Chem. B* **119**, 11068–11078 (2015).

Theory for Optical Response in Nanostructures and its Application to Functional Nanodevices

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Keywords Optical Near-Field, Light-Matter Interaction, Nanodevices

Optical response of molecules is undoubtedly essential for understanding their physicochemical properties. In conventional theoretical approaches to optical response of molecules, two conditions are usually assumed:

(i) Wavelength of incident light is considered to be much longer than molecular size, *i.e.*, dipole approximation. Thus, a target molecule is well approximated by a point dipole and the dipole feels a uniform electromagnetic field.

(ii) Electric polarization in a molecule induced by incident-light excitation inevitably generates a new electromagnetic field, referred to as an “optical near-filed.” However, such a self-consistent light-matter (LM) interaction between electron and electromagnetic field dynamics is ignored.

Recent development of nanofabrication and nano-optical techniques requires a more general optical response theory fully taking account of *nonuniform and self-consistent* LM interactions.

We have developed a generalized theoretical description of full (nonuniform and self-consistent) LM interactions with the aim of understanding the optical near-field excitation dynamics in nanostructures of more than ten-nanometers in size. Electron dynamics in nanostructures interacting with an electromagnetic field is described by the time-dependent Kohn-Sham (TDKS) equation, whereas electromagnetic field dynamics is represented by the microscopic Maxwell’s equations. The nonuniform LM interaction is taken into account in the vector potential and the self-consistent LM interaction is described by solving the electron and electromagnetic field coupled equations self-consistently. The coupled equations are solved numerically by using our developed computational program (GCEED: *Grid-based Coupled Electron and Electromagnetic field Dynamics*). Our computational approach is based on a finite-difference method in real-time and real-space. Since the approach employs very simple algorithms, it is very suitable for massively parallelized computations.

Very recently, we also started the theoretical studies of computational design of catalytic metal clusters supported on bulk surfaces. The simulations were carried out by using the first-principles molecular dynamics (MD) approach, *i.e.*, Car-Parrinello MD simulations. The theoretical approach allows us to treat dynamical chemical reaction processes taking account of the effects of temperature and nonequilibrium interactions between clusters and supports.

Selected Publications

- K. Nobusada and K. Yabana, “Photoinduced Electric Currents in Ring-Shaped Molecules by Circularly Polarized Laser Pulses,” *Phys. Rev. A* **75**, 032518 (7 pages) (2007).
- T. Iwasa and K. Nobusada, “Nonuniform Light-Matter Interaction Theory for Near-Field-Induced Electron Dynamics,” *Phys. Rev. A* **80**, 043409 (11 pages) (2009).
- K. Nobusada and T. Iwasa, “Oligomeric Gold Clusters with Vertex-Sharing Bi- and Triicosahedral Structures,” *J. Phys. Chem. C* **111**, 14279–14282 (2007).
- M. Noda, K. Ishimura, K. Nobusada, K. Yabana and T. Boku, “Massively-Parallel Electron Dynamics Calculations in Real-Time and Real-Space: Toward Applications to Nanostructures of More than Ten-Nanometers in Size,” *J. Comput. Phys.* **265**, 145–155 (2014).

1. Two-Photon Absorption Induced by Electric Field Gradient of Optical Near-Field and its Application to Photolithography[1)]

An electric field gradient is an inherent property of the optical near-field (ONF). In this study, we have verified that the electric field gradient of the ONF intrinsically leads to two-photon absorption, demonstrating the optical response of a closely-placed dielectric nanoparticle and quantum dot system. The theoretical calculations were carried out by using a density matrix formalism and a classical Lorentz model. The electric field gradient of the ONF was found to cause two-photon absorption by an unusual mechanism. Furthermore, the absorption exhibits a non-monotonic dependence on the spatial arrangement of the nanosystem, completely different from that of conventional two-photon absorption induced by an intense electric field. The present two-photon absorption process was illustrated in a previous experimental observation, by reinterpreting the results of ONF photolithography. The present idea of the two-photon absorption due to the electric field gradient is not limited to the model system considered here. The idea provides a basis for fundamental optical responses in nanostructures and paves the way for the ONF excitation dynamics that are completely different from those of conventional optical response processes.

2. Reaction Pathway and Free Energy Landscape of Catalytic Oxidation of Carbon Monoxide Operated by a Novel Supported Gold–Copper Alloy Cluster[2)]

An insight into the catalytic activities of pure gold (Au_8) and gold-alloy ($CuAu_7$) clusters supported on either MgO(100) or graphene has been undertaken in the search for an efficient, yet commercially appealing production of Au-based nanocatalysts. The present set of first-principles dynamical simulations shows that the gold and gold-copper alloy clusters destabilize to various extents on MgO but preserve their structures on the graphene support at room temperature. Consequently, the Cu atom remains embedded inside the Au cluster on MgO, whereas it can be easily exposed on the cluster surface on the graphene substrate. This feature appears to be a general key issue to trigger the catalytic reaction and discloses new perspectives for a rational synthesis of supported Au-based catalysts relying on the intrinsic chemical character of Cu which possesses a stronger affinity to oxygen than Au. Indeed, the Cu atom acts as an active site for the approach of O_2 and keeps the molecule bound to the cluster. We clarified that the catalytic oxidation of CO occurs on the graphene-supported $CuAu_7$ in a highly selective Langmuir-Hinshelwood type reaction, addressing the long-standing controversy about the actual reaction mechanism for this type of catalysis. Our findings contribute to the development of efficient and commercially appealing supported alloy clusters driven by a proper choice of dopants and supports, thus reducing the use of expensive gold.

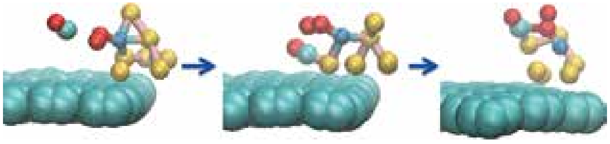

Figure 1. A first step of the Langmuir-Hinshelwood type reaction on $CuAu_7$ supported by graphene, obtained via Blue-Moon ensemble simulations. CO approaches the gold surface and reacts with O_2 anchored on the Cu active site, forming an intermediate for the subsequent CO_2 desorption.

3. Control of Optical Response of a Supported Cluster on Different Dielectric Substrates[3)]

We developed a theoretical approach for photo-induced electron dynamics at an interface, approximating a substrate as a dielectric continuum. Because electron dynamics is treated in real-time and real-space, the approach is applicable to various optical processes. We calculated optical absorption of Ag_n (n = 2, 54) supported on a dielectric substrate with a Drude-type dielectric function. Changes in ω_p and γ of the substrate differently altered the spectral peak position and intensity. By analyzing the time-dependent induced dipole and spatial configuration of induced electron density, we clarified the mechanism underlying spectral changes, relating to experimental results obtained in many research areas. Shifts in spectral peaks of Ag_2 were mainly determined by the strength of attractive and repulsive interactions with the substrate, and decreases in peak intensity were due to energy dissipation into the substrate. These peak shifts and intensity changes are related to the real and imaginary parts of $\varepsilon-1/\varepsilon+1$, respectively. We extended the approach to a nanostructure, Ag_{54}, and found another mechanism for changes in intensity, which is related to the real part of $\varepsilon-1/\varepsilon+1$. The spectral peak for Ag_{54} increases through interactions with the Ag substrate because of collective oscillations of electrons. The present method and the resulting insights contribute to a basic understanding of optical processes at an interface and to the development of optical devices that can be controlled by electronic properties of a substrate.

References

1) M. Yamaguchi, K. Nobusada, T. Kawazoe and T. Yatsui, *App. Phys. Lett.* **106**, 191103 (2015).

2) K. Koizumi, K. Nobusada and M. Boero, *J. Phys. Chem. C* **119**, 15421–15427 (2015).

3) K. Iida, M. Noda and K. Nobusada, *J. Chem. Phys.* **142**, 214702 (2015).

Advanced Electronic Structure Theory in Quantum Chemistry

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Keywords Electronic Structure Theory, Quantum Chemistry, Computational Chemistry

Computational quantum chemistry, that is, practicing quantum chemical theory using computers, is now considered to be a powerful means to provide detailed analysis of chemical phenomena. The focus of our group is to develop methods and algorithms of molecular electronic structure calculations, which are capable of supplying electronic-level interpretation and reliable prediction of chemical characters, reactivity, energetics, and spectroscopic properties of molecular systems. Also, we are interested in applying the methods to challenging chemical systems. Recently, we have developed advanced multireference methods to describe highly-correlated many-electron wavefunction, which cannot be qualitatively accounted for with mean-field or one-electron theory (*e.g.*, density functional theory). The multireference wavefunction need be represented with a quantum superposition of multiple electron configurations; however, this gives rise to a high computational expense because the degree of the superposition is in general exponentially dependent on the system size. We approach the multireference problems using the density matrix renormalization group (DMRG), which is originally a method of condensed matter physics to solve strong correlation phenomena in physical models. We developed an efficient implementation for adapting DMRG to quantum chemical calculation, in which the DMRG is exploited to describe static correlation in combination with the complete active space (CAS) model. Our DMRG-based methods have shown to be capable of handling very large correlation space, which far exceeds the limitation of conventional methods. We have further introduced a scheme to additively account for dynamic correlation on top of active-space DMRG wavefunction. Using these methods, we carried out chemical applications to multireference electronic systems, ranging from organic material molecules, such as radicals of graphene nanoribbons, to transition metal complexes, such as tetranuclear manganese cluster.

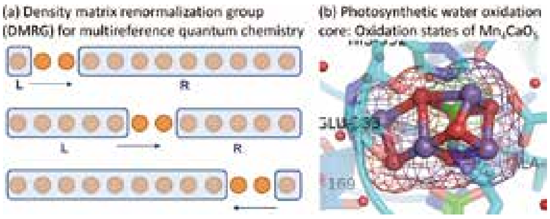
(a) Density matrix renormalization group (DMRG) for multireference quantum chemistry
(b) Photosynthetic water oxidation core: Oxidation states of Mn_4CaO_5

Figure 1. (a) Algorithm of density matrix renormalization group (DMRG) and (b) Its application to manganese cluster.

Selected Publications

- Y. Kurashige and T. Yanai, "High-Performance *Ab Initio* Density Matrix Renormalization Group Method: Applicability to Large-Scale Multireference Problems for Metal Compounds," *J. Chem. Phys.* **130**, 234114 (21 pages) (2009).
- W. Mizukami, Y. Kurashige and T. Yanai, "More π Electrons Make a Difference: Emergence of Many Radicals on Graphene Nanoribbons Studied by *Ab Initio* DMRG Theory," *J. Chem. Theory Comput.* **9**, 401–407 (2013).
- Y. Kurashige, G. K-L. Chan and T. Yanai, "Entangled Quantum Electronic Wavefunctions of the Mn_4CaO_5 Cluster in Photosystem II," *Nat. Chem.* **5**, 660–666 (2013).

1. Fully Internally Contracted Multireference Configuration Interaction Theory Using Density Matrix Renormalization Group

We present an extended implementation of the multireference configuration interaction (MRCI) method combined with the quantum-chemical density matrix renormalization group (DMRG). In the previous study, we introduced the combined theory, referred to as DMRG-MRCI, as a method to calculate high-level dynamic electron correlation on top of the DMRG wavefunction that accounts for active-space (or strong) correlation using a large number of active orbitals. The previous implementation achieved the MRCI calculations with the active space (24*e*,24*o*), which are deemed the record largest, whereas the inherent $O(N^9)$ complexity of computation was found a hindrance to use further large active space. In this study, an extended optimization of the tensor contractions is developed by explicitly incorporating the rank reduction of the decomposed form of the cumulant-approximated tensors into the factorization. It reduces the computational scaling (to $O(N^8)$) as well as the cache-miss penalty. The new DMRG-MRCI implementation is applied to the determination of the stability of the iron(IV)-oxo porphyrin relative to the iron(V) electronic isomer (electromer) using the active space (29*e*,29*o*) (including four second d-shell orbitals of iron) with triple-*z*-quality atomic orbital basis sets. The DMRG-MRCI model is shown to favor the triradicaloid iron(IV)-oxo state as the lowest-energy state and characterize the iron(V) electromer as thermally inaccessible, supporting the earlier experimental and density functional studies. This conflicts with the previous MR calculations using the restricted active space second-order perturbation theory with the similar-size active space (29*e*,28*o*) reported by Pierloot *et al*. [M. Radon, E. Broclawik, and K. Pierloot, *J. Chem. Theory Comput.* **7**, 898 (2011)], showing that the hypothetical iron(V) state indicated by recent laser flash photolysis (LFP) studies is likely thermally accessible because of its underestimated relative energy.

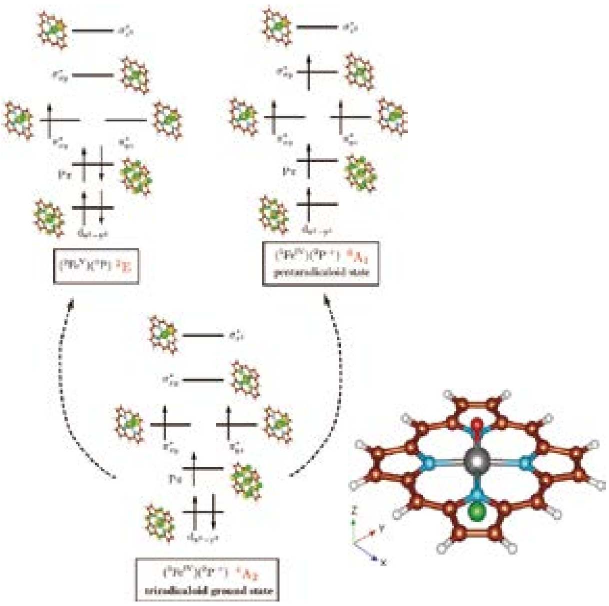

Figure 2. Electronic isomers of FeO(P)Cl molecule and their electronic configurations $^4A_2$ is a formal ground state; however, recent LFP analysis suggests the presence of the stable $^6A_1$ state.

2. Scalar Relativistic Calculations of Hyperfine Coupling Constants Using *Ab Initio* DMRG[5)]

We have developed a new computational scheme for high-accuracy prediction of the isotropic hyperfine coupling constant (HFCC) of heavy molecules accounting for the high-level electron correlation effects as well as the scalar-relativistic effects. For electron correlation, we employed the *ab initio* DMRG method in conjunction with a complete active space model. The orbital-optimization procedure was employed to obtain the optimized orbitals required for accurately determining the isotropic HFCC. For the scalar-relativistic effects, we initially derived and implemented the Douglas-Kroll-Hess hyperfine coupling operators up to the third order by using the direct transformation scheme. A set of *4d* transition metal radicals consisting of Ag atom, PdH, and RhH_2 were chosen as test cases. Good agreement between the isotropic HFCC values obtained from DMRG/DKH3 and experiment was archived.

References

1) Y. Kurashige and T. Yanai, *Bull. Chem. Soc. Jpn.* **87**, 1071–1073 (2014).
2) T. Yanai, Y. Kurashige, W. Mizukami, J. Chalupský, T. N. Lan and M. Saitow, *Int. J. Quantum Chem.* **115**, 283–299 (2015).
3) J. Chalupský, T. A. Rokob, Y. Kurashige, T. Yanai, E. I. Solomon, L. Rulíšek and M. Srnec, *J. Am. Chem. Soc.* **136**, 15977–15991 (2014).
4) Y. Kurashige, J. Chalupský, T. N. Lan and T. Yanai, *J. Chem. Phys.* **141**, 174111 (13 pages) (2014).
5) T. N. Lan, Y. Kurashige and T. Yanai, *J. Chem. Theory Comput.* **11**, 73–81 (2015).
6) Y. Ishikawa, S. Kimura, K. Takase, K. Yamamoto, Y. Kurashige, T. Yanai and T. Murahashi, *Angew. Chem., Int. Ed.* **54**, 2482–2486 (2015).
7) T. N. Lan, J. Chalupský and T. Yanai, *Mol. Phys.* **113**, 1750–1767 (2015).
8) T. Yanai, G. I. Fann, R. J. Harrison and G. Beylkin, *Phys. Chem. Chem. Phys.* (12 pages) (2015). DOI: 10.1039/c4cp05821f
9) S. Horiuchi, Y. Tachibana, K. Yamamoto, S. Kawamata, K. Takase, T. Matsutani, K. Masai, Y. Kurashige, T. Yanai and T. Murahashi, *Nat. Commun.* **6**, 6742 (8 pages) (2015).

Award

KURASHIGE, Yuki; The Chemical Society of Japan Award for Young Chemists 2014.

Theoretical Study on Photochemistry and Catalysis

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Keywords Quantum Chemistry, Photophysical Chemistry, Heterogeneous Catalysis

We develop the accurate electronic structure theories and investigate the photochemistry and catalysis theoretically. Currently, our focuses are following research subjects.

(1) Coupled cluster theory for excited states of large system

We develop the coupled cluster theories and their efficient computational algorithm aiming at large-scale calculations of molecular excited states. We also develop the basic theories and methodologies that are useful for fundamental chemistry and applied chemistry; for example, PCM SAC-CI method for effectively describing the solvent effects on excited states, CAP/SAC-CI method for locating metastable resonance states, general-R method for multiple excited states, and active-space method for efficiently describing complex electronic states.

(2) Heterogeneous catalysis

Metal nanoclusters supported by metal oxides or polymers achieve highly efficient catalytic reactions. We study the catalytic activity of these complex systems by means of quantum chemical calculations and informatics theories. We have elucidated the importance of the perimeter sites at hetero-junction of Ag nanocluster supported by alumina surface in terms of H_2 activation, the mechanism of methanol oxidation on Au:PVP and the unique coupling reactions on Au/Pd:PVP. We proceed these works in the project of Elements Strategy Initiative for Catalysts and Batteries (ESICB).

(3) Photophysical chemistry

Our accurate electronic structure theories are applied to wide varieties of theoretical studies and sometimes in cooperation with experiments on the photophysical properties and excited-state dynamics of nano-bio systems like photo-electronic devices, photofunctional molecules, and biosensors. Target molecules include nanocarbons like fullerenes, near-IR absorbing phthalocyanine congeners, dye-sensitized solar cells, organometallic compounds for artificial photosynthesis, biological chemosensors, and bio-imaging probes.

(4) Theoretical spectroscopy

New quantum states, single-site and two-site double-core hole states, have been observed owing to the recent development of free electron laser and coincidence spectroscopy. We have proposed new chemical concept regarding the physical properties or relaxation processes of these quantum states in cooperation with experiments. We also perform accurate theoretical analysis for the state-of-the-art molecular spectroscopy; for example, the electronic transitions in the FUV region by ATR-FUV spectroscopy and the excited-state relaxation processes by pump–probe spectroscopy.

Selected Publications

- R. Cammi, R. Fukuda, M. Ehara and H. Nakatsuji, "SAC-CI Method in the Polarizable Continuum Model-Theory for Solvent Effect on Electronic Excitation of Molecules in Solution," *J. Chem. Phys.* **133**, 024104 (24 pages) (2010).
- N. Berrah, M. Tashiro, M. Ehara *et al.*, "Double Core-Hole Spectroscopy for Chemical Analysis with an Intense X-Ray Femtosecond Laser," *Proc. Natl. Acad. Sci. U.S.A.* **108**, 16912–16915 (2011).
- M. Ehara and T. Sommerfeld, "CAP/SAC-CI Method for Calculating Resonance States of Metastable Anions," *Chem. Phys. Lett.* **537**, 107–112 (2012).
- P. Hirunsit, K. Shimizu, R. Fukuda, S. Namuangruk, Y. Morikawa and M. Ehara, "Cooperative H_2 Activation at Ag Cluster/θ-Al_2O_3 Dual Perimeter Sites: A DFT Study," *J. Phys. Chem. C* **118**, 7996–8006 (2014).

1. Complex Absorbing Potential (CAP) for Resonance States

Complex absorbing potentials (CAP) have been successfully applied in many contexts from nuclear physics, over vibrational predissociation and reactive scattering phenomena, to electronically metastable states. In the electronic structure, CAPs are used to characterize resonances, such as temporary anions and dianions, core ionized states (Auger decay), and molecules subjected to field ionization.

We have introduced new CAP forms and systematically examined their performances,$^{1)}$ for example, in double-bond and heteroaromatic molecules (Figure 1). The advantage of new CAPs is that they warp perfectly around the molecular systems with side chain or any monomer of a cluster.

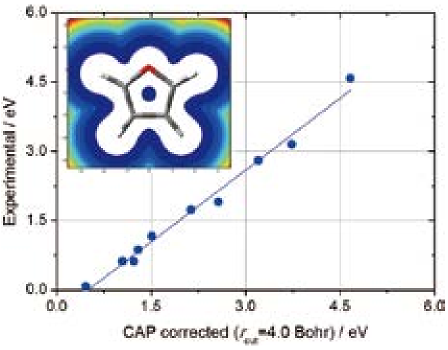

Figure 1. Correlation between calculated resonance energy and observed energy. A smooth Voronoi potential (example shown in the inset of the figure) was developed.

2. Modeling Molecular Systems at Extreme Pressure in Various Electronic States

Novel molecular photochemistry can be developed by combining high pressure and laser irradiation. For studying such high-pressure effects (order of GPa) on the confined electronic ground and excited states, we extend the PCM (polarizable continuum model) SAC (symmetry-adapted cluster) and SAC-CI (SAC-configuration interaction) methods to the PCM-XP (extreme pressure) framework.

The PCM-XP SAC/SAC-CI method was applied to furan (C_4H_4O) in cyclohexane at high pressure (1–60 GPa).$^{2)}$ The excitation energies of furan in cyclohexane show blue shift with increasing pressure, yet the extents of the blue shift significantly depend on the character of the excitations (Figure 2). The energy ordering of the lowest Rydberg and valence states alters under high-pressure. The pressure effects on the electronic structure are two-fold: A confinement of the molecular orbital and a significant change in valence-Rydberg mixing along the pressure.

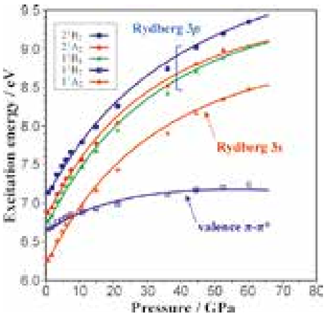

Figure 2. Variation of the excitation energies for furan calculated by the PCM-XP SAC-CI.

3. Bond Activation on Bimetallic Alloy Nanoclusters

Gold-Palladium (Au/Pd) bimetallic nanocluster (NC) catalysts have been extensively investigated because of their wide varieties of catalytic activity for various substrates. Recently, we have developed new catalysts for C–Cl bond activation under mild condition using Au/Pd NP supported on poly-*N*-vinylpyrrolidone (PVP); the Ullmann coupling of aryl chloride (ArCl).$^{3)}$

We have investigated the C–Cl bond activation on Au/Pd NC for the oxidative addition of ArCl, which is a key step of this homocoupling reaction (Figure 3).$^{4)}$ Some stable cage structures and spin states of Au/Pd NCs were found by using genetic algorithm (GA) and DFT calculations. Several low-lying oxidative addition pathways were obtained and some of them are thermally accessible via spin crossing and internal conversion.

The present computational protocol using GA combined with the DFT calculations is useful for investigating the structures and reactivity of the bimetallic NCs.

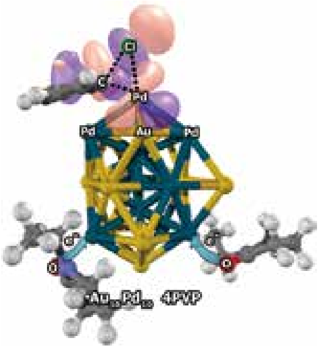

Figure 3. C–Cl bond activation on bimetallic Au/Pd nanocluster coordinated by PVP (polyvinylpyrolidon).

References

1) T. Sommerfeld and M. Ehara, *J. Chem. Phys.* **142**, 034105 (2015); T. Sommerfeld and M. Ehara, *J. Chem. Theory Comput.*, in press.
2) R. Fukuda, M. Ehara and R. Cammi, *J. Chem. Theory Comput.* **11**, 2063–2076 (2014).
3) R. N. Dhital, C. Kamonsatikul, E. Somsook, K. Bobuatong, M. Ehara, S. Karanjit and H. Sakurai, *J. Am. Chem. Soc.* **134**, 20250–20253 (2012).
4) B. Boekfa, E. Pahl, N. Gaston, H. Sakurai, J. Limtrakul and M. Ehara, *J. Phys. Chem. C* **118**, 22188–22196 (2014).

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* IMS International Internship Program

Development of New Molecular Dynamics Algorithms for Biomolecular Systems

Department of Theoretical and Computational Molecular Science
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Education

1998	B.S. Keio University
2002	Ph.D. Keio University

Professional Employment

2002	Postdoctoral Fellow, The University of Tokyo
2002	Research Associate, Institute for Molecular Science
2004	Research Associate, The Graduate University for Advanced Studies
2006	Research Lecturer, Nagoya University
2008	Research Assistant, Rutgers University
2009	Assistant Research Professor, Rutgers University
2009	Associate Professor, Institute for Molecular Science
	Associate Professor, The Graduate University for Advanced Studies

Award

2014	Academic Award of the Molecular Simulation Society of Japan

Member

Assistant Professor	ITOH, Satoru G.
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Keywords Molecular Dynamics Simulation, Protein, Amyloid

Biomolecules such as proteins and peptides have complicated free-energy landscape with many local minima. The conventional canonical-ensemble molecular dynamics (MD) simulations tend to get trapped in a few of the local-minimum states. To overcome these difficulties, we have proposed new generalized-ensemble algorithms, such as replica-permutation method. We apply these methods to proteins and peptides and try to predict the native structures of proteins as in Figure 1.

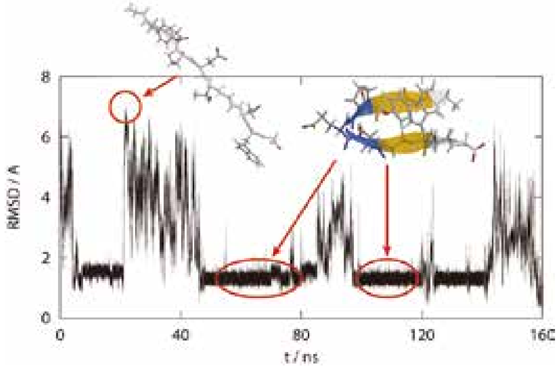

Figure 1. Time series of protein folding simulation.

We are also interested in amyloid fibrils, which are insoluble aggregates of misfolded fibrous proteins and associated with more than 20 human neurodegenerative diseases (Figure 2). For example, Alzheimer's disease is related to amyloid-β (Aβ) peptides. To overcome these diseases, it is essential to understand amyloid genesis and disruption. We perform such MD simulations of amyloid fibrils.

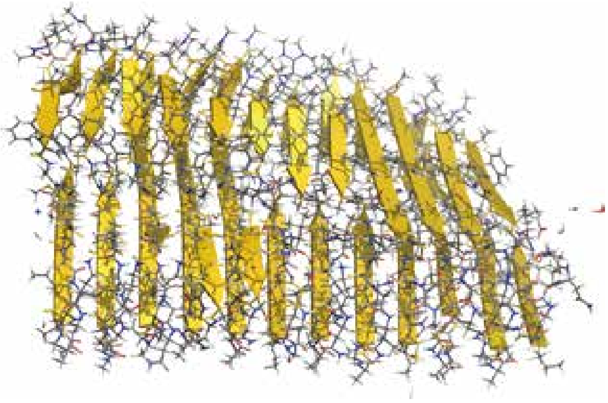

Figure 2. Snapshot of amyloid fibril.

Selected Publications

- H. Okumura and S. G. Itoh, "Amyloid Fibril Disruption by Ultrasonic Cavitation: Nonequilibrium Molecular Dynamics Simulations," *J. Am. Chem. Soc.* **136**, 10549–10552 (2014).
- S. G. Itoh and H. Okumura, "Replica-Permutation Method with the Suwa-Todo Algorithm beyond the Replica-Exchange Method," *J. Chem. Theory Comput.* **9**, 570–581 (2013).
- Y. Mori and H. Okumura, "Pressure-Induced Helical Structure of a Peptide Studied by Simulated Tempering Molecular Dynamics Simulations," *J. Phys. Chem. Lett.* **4**, 2079–2083 (2013).
- H. Okumura, "Temperature and Pressure Denaturation of Chignolin: Folding and Unfolding Simulation by Multibaric-Multithermal Molecular Dynamics Method," *Proteins* **80**, 2397–2416 (2012).

1. Dimerization Process of Amyloid-β(29-42) by the Hamiltonian Replica-Permutation Molecular Dynamics Simulations

In order to investigate the dimerization process and conformations of amyloid-β peptides, we applied the Hamiltonian replica-permutation method, which is a better alternative to the Hamiltonian replica-exchange method, to two amyloid-β(29-42) molecules in explicit water solvent.$^{1)}$ At the first step of the dimerization process, two amyloid-β(29-42) molecules came close to each other and had intermolecular sidechain contacts. When two molecules had the intermolecular sidechain contacts, the amyloid-β(29-42) tended to have intramolecular secondary structures, especially β-hairpin structures as in Figure 3. The two molecules had intermolecular β-bridge structures by coming much closer at the second step of the dimerization process. Formation of these intermolecular β-bridge structures were induced by the β-hairpin structures. The intermolecular β-sheet structures elongated at the final step. Structures of the amyloid-β(29-42) in the monomer and dimer states are also shown with the free-energy landscapes, which were obtained by performing efficient sampling in the conformational space in our simulations.

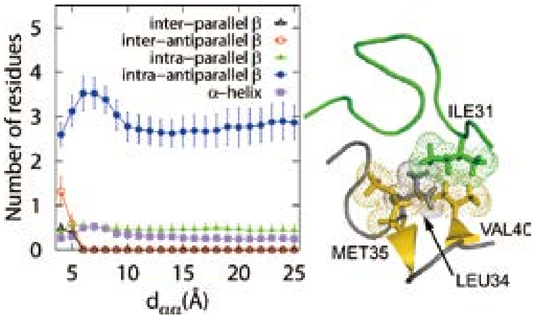

Figure 3. Ensemble-averages of the numbers of residues that have secondary structures at the corresponding intermolecular distance $d_{\alpha\alpha}$ (left) and a snapshot of a representative conformation at $d_{\alpha\alpha}$ = 8 Å (right).

2. Molecular Dynamics of the Structural Changes of Helical Peptides Induced by Pressure

An AK16 peptide and a C-peptide analog are experimentally known to form more helical structures under high pressure conditions than those at atmospheric pressure, even though most proteins usually unfold at high pressure as in Figure 4. To understand the pressure-induced structural changes of the two peptides, molecular dynamics simulations with the simulated tempering method for the isobaric-isothermal ensemble were performed in a wide pressure range from 0.1 MPa to 1.4 GPa.$^{2)}$ We found that the fraction of the folded state decreases once and then increases with increasing pressure for both peptides. The partial molar volume change of both peptides from the folded state to the unfolded state increases monotonically from a negative value to a positive value as pressure increases. By calculating the radius of gyration and interatomic distances of the AK16 peptide and the C-peptide analog, we found that these peptides are compressed under high-pressure conditions, which causes the folded state to be more stable at high pressure. Furthermore, we found that the salt bridge of the C-peptide analog is broken under high pressure.

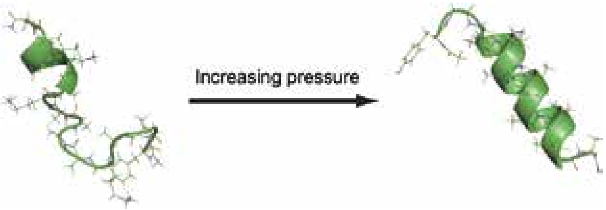

Figure 4. Coil structure of an AK16 peptide (left) and the helically folded structure of this peptide (right).

3. Comparison of Replica-Permutation Molecular Dynamics Simulations with and without Detailed Balance Condition

In the replica-permutation method (RPM), temperatures are not only exchanged between two replicas but also permutated among more than two replicas using the Suwa–Todo algorithm, which minimizes the rejection ratio in Monte Carlo trials. We verify the sampling efficiency of RPM that adopts Suwa–Todo algorithms with and without a detailed balance condition (DBC).$^{3)}$ To compare these techniques, molecular dynamics simulations of RPM with and without the DBC and the replica-exchange method (REM) were carried out for a chignolin molecule in explicit water. Although no difference in the numbers of folding and unfolding events was observed, the numbers of tunneling events of the two RPM simulations were larger than that of REM. This indicates that the minimization of the rejection ratio by the Suwa–Todo algorithm in RPM realizes efficient sampling. Furthermore, the sampling efficiency was slightly higher in the RPM without the DBC than in that with the DBC. The reason for this difference is also discussed.

References

1) S. G. Itoh and H. Okumura, *J. Phys. Chem. B* **118**, 11428–11436 (2014).
2) Y. Mori and H. Okumura, *Proteins* **82**, 2970–2981 (2014).
3) H. Nishizawa and H. Okumura, *J. Phys. Soc. Jpn.* **85**, 074801 (6 pages) (2015).

Award

OKUMURA, Hisashi; Academic Award of the Molecular Simulation Society of Japan (2014).

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* carrying out graduate research on Cooperative Education Program of IMS with Nagoya University

Theory and Computation of Reactions and Properties in Solutions and Liquids

Department of Theoretical and Computational Molecular Science
Division of Computational Molecular Science

ISHIDA, Tateki
Assistant Professor

We focus on the projects both on ultrafast photoinduced electron energy transfer in the excited state in solution and on ionic liquids (ILs). The project on photoinduced electron energy transfer processes in the excited state in solution is aimed at the development of a theoretical method to investigate electron energy transfer including solvent motion and dynamics. On the other hand, ILs' projects are focused on the study of dynamical properties on ionic liquids using molecular dynamics simulation technique.

1. The Theoretical Investigation of Photoinduced Electron Energy Transfer Processes in the Excited State in Solution[1)]

We have developed a procedure for describing the time-dependent evolution of the electronic structure of a solute molecule in solution, coupling an electronic structure theory with solvent motion. We have extended this method for studying electron energy transfer processes in the excited state in solution. It is shown that the coupling between solvation dynamics and a fast intramolecular electron energy transfer is likely to play an important role in the emergence of photo-induced unique functionalities in biochemical and metal complex systems.

2. Investigations of Dynamical Properties on Ionic Liquids[1–2)]

In particular, we focus on the dynamical properties on ionic liquids (ILs). With molecular dynamics simulation procedure, it have been found out that ILs show unique collective dynamics. We have investigated interesting dynamical heterogeneity in ILs at room temperature. Also, we have studied spatial heterogeneity.

References

1) T. Ishida, *AIP Conference Proceedings for 8th International Conference of Computational Methods in Sciences and Engineering(ICCMSE) 2010*, *AIP Conf. Proc.* **1642**, pp. 518–521 (2015).
2) T. Ishida and H. Shirota, *J. Phys. Chem. B* **117**, 1136–1150 (2013).

Visiting Professors

Visiting Professor

TEN-NO, Seiichiro *(from Kobe University)*

New Frontier of Hybrid Stochastic and Deterministic Electronic Structure Approaches

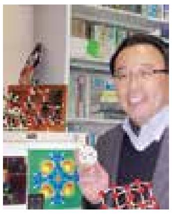
The vast majority of ab initio electronic structure methods are on the basis of deterministic disciplines, in which a compactification of an N-factorial CI expansion is of main interest. Nevertheless, the way to calculate strongly correlated systems with quasi-degeneracy and general excited states accurately still remains open. These objectives are of significant importance for entangled electronic states involving photoinduced phenomena in biochemistry and energy conversion processes in chemistry. We have recently developed the model space quantum Monte Carlo (MSQMC) method crossing the effective Hamiltonian formalism and full configuration interaction (FCI) QMC [*ST*, *J. Chem. Phys.* **138**, 164126 (2013)]. The method sidesteps the negative sign problem in QMC arising from quasi-degeneracy transcending the storage limitation for CI vectors. Promising results are obtained for the FCI potential energy curves of various excited states. We further extend MSQMC to energy independent partitioning (EIP) that enable us to obtain all of the FCI solutions in the model space simultaneously.

Visiting Professor

TAKADA, Shoji *(from Kyoto University)*

Computational Studies of Biomolecular Systems

I am studying in the area of computational molecular biophysics, primarily focusing on protein structure and dynamics. Even though thousands of X-ray crystal structures may provide impression that biomolecules are rigid material, in reality they are nano-scale molecules that work under thermal noise and, as such, they are dynamic. Given many crystal structures as snapshots, my ultimate goal is to understand dynamical functions of these molecules via computational analysis. Specifically, using coarse-grained molecular modeling approach, we study interplay between conformational dynamics and protein function, for adenylate kinase as a model protein. Adenylate kinase exerts large-amplitude motion that couples with binding to substrates, ATP and AMP. After binding and structural change, it catalyzes chemical reaction to obtain 2ADP, which is then released coupling with conformational dynamics. Modeling the entire process of this enzyme can be an ideal computational model for complete cycles of molecular machines.



Visiting Associate Professor

SUGIMOTO, Manabu *(from Kumamoto University)*

Computational Molecular Science for Chemical Design and Engineering

The quantum chemical method is a powerful and insightful tool for analyzing and predicting molecular structures and chemical phenomena. Our group is interested in applying electronic-structure methods for investigating molecular functions that are of practical importance. Our on-going research is twofold: One is direct application of the quantum methods. For example, we have recently carried out the calculations to characterize electronic excitations in supramolecular systems, and developed a computational scheme to study elastic deformation of a molecule by external force. We are also studying materials related to energy conversion such as hydrogen-production catalysts and those in photovoltaics. Another research is for development of chemoinformatics through which one would be able to learn, understand, investigate, predict, and design molecules and their chemistries. We are developing a computer system on the basis of our original electronic-structure database and new search engines. Our contribution is intended to enrich usefulness and uniqueness of Computational Molecular Science.